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Spintronics and quantum computation

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Abstract : An effort has been made to discuss a new class of devices based on electron spin. In the present review, several proposed spintronic [illegible] have been studied which can help in providing new functions and an improvement over the existing electronic devices.

Keywords : Spintronics, spin polarized transport, quantum computation

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Plan of the Article

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1. Introduction

The recent technology in electronic systems is based on the principle of generating or controlling electrical current by exploiting the charge nature of electrons, *i.e.* by steering up the motion of the charge carriers through their interaction with external electric or electromagnetic fields. To make these electronic systems smaller, versatile and more robust than these currently making up silicon chips and circuits, physicists are trying to exploit the 'spin' of the electron rather than the charge. In fact, the spin of the electrons has attracted renewed interest towards the variety of new devices that combine logic, storage and sensor applications. The other important area of these spin based devices is in the field of computation. The spin dependent quantum computation based on electronic solid state devices, changing the prospective of information technology.

During the past five decades, the world witnessed a revolution based on a digital logic of electronics. From the earliest transistor to the remarkably powerful microprocessor in our desktop computer, most electronic devices have employed circuits that express data as binary digits, or bits- ones and zeros represented by the existence or absence of electric charge. Further, the communication between microelectronic devices occurs due to the binary flow of electric charges. The growth of microelectronics is often popularly summarized in Moore's law, which suggests that microprocessors will double in power within every 18 months as electronic devices shrink and more logic is packed into every chip. According to current pace of

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miniaturization Moore's law will run out of momentum as one day, the size of features on the chip approaches the dimension of the atoms. Hence this has been called the end of the silicon road map. For this reason, scientists are trying to enhance the multifunctionality of devices for example, carrying out processing and data storage on the same chip.

2. Spintronics

Electron has intrinsic quantity of angular momentum called spin. The revolution of an electron around the given axis originates this angular momentum. The motion of the spin creates magnetic moment and hence the magnetic field. So these spin acts as a tiny bar magnet lined up with the spin axis. The spin can be represented with a vector notation. This vector may be 'up' or 'down' depending on the spinning of electron like a top spinning anticlockwise (up) or clockwise (down) (Figure 1). The external parameters influence this spin orientation, for example, these two orientations of spin have different energies when magnetic field is present. Besides the electron spin, neutron and proton also have spin and hence the nucleus has resultant spin.

Figure 1. Electron precession leads to electron spin · clockwise (up) and anticlockwise (down)

Spintronics, (spin electronics), refers to the study of the role played by electron (or nucleus) spin in solid state physics, and devices that specifically exploit spin properties instead of or in addition to the charge degree of freedom [1]. There are a lot of advantages in exploiting the spin degree of freedom in electronic systems. These spin-based devices would have higher data processing speed and integration densities and lower electric power consumption compared to conventional semiconductor devices. These devices can very well replace and complement various conventional electronic devices with improved performance. However, to successfully incorporate spin into existing semiconductor technology, one has to resolve some of the technical issues such as efficient injection, transportation, precise control and manipulation, and detection of spin polarization as well as spin polarized current.

In an ordinary electric circuit, the spin are oriented randomly and have no effect on electron flow. However, spintronics devices create spin-polarized current and use the spin to control current flow. All spintronics devices act according to the simple scheme:

(i) Information is stored into spin depending upon particular spin orientation (up or down),

(ii) The spin, being attached to mobile electrons, carry the information along a wire, and

(iii) The information is read at terminal.

Now the question is why this spin-dependent transport is so important. The answer is that the spin orientation of conduction electrons survives for a relatively long time (nanosecond). This property of spin based system makes spintronics devices particularly attractive for memory storage, magnetic sensor applications, and potentially for quantum computing, where electron spin would present as a bit of information.

Spintronics , which is also known as magneto-electronics is a field of active control of carrier spin dynamics and transport in electronic materials (particularly, but not necessarily limited to semiconductors). The existing technologies such as GMR (Giant magnetoresistance)-based memory devices [1,2] and spin valves are elementary spintronic devices. In these devices, the role of spin is passive *i.e.* the alignment of electron spin does not changes with time. The size of the system resistance or tunneling current depends upon the spin direction that is controlled by local magnetic fields. The main goal of spintronics is to go beyond passive spin devices, and introduce applications based on the active control of spin dynamics. Such active control of spin dynamics is envisioned to lead novel quantum-mechanical enabling technologies such as spin transistor [3], spin filter [4], spin valves [5,6], GMR based new memory devices [1,2,7-10] and perhaps eventually quantum information processing [11-13] and quantum computation [14-20]. We will discuss these devices one by one in the proceeding sections.

The two important physical principles underlying the current interest in spintronics are the quantum mechanical nature of spin as a dynamic variable and the long relaxation or coherence time associated with spin states (compared with the ordinary momentum states). The fact is that the carrier spin in semiconductors can easily be manipulated noninvasively by using local magnetic fields, by applying external electric fields through controlled gates, and by shining polarized light [21].

3. Spin-related phenomena

The brief phenomenon of spin and spintronics is discussed in previous section. In this section, we will discuss various spin-related phenomena and spin-based devices.

(i) Spin relaxation and decoherence :

The great promise of spintronics technology is based upon the fundamental ability of electron spin in electronic materials to preserve coherence for relatively long time [22,23]. Here, we mean with the coherence is that the electron spin remain in phase during its motion in the device. A typical electron 'remembers' its initial spin orientation for a nanosecond ; this is known as spin life time or spin relaxation time (T_1). This time scale is indeed longer compared to electron momentum relaxation (~femtosecond) time. Perhaps, a more revealing quantity than spin life time is spin diffusion length (L_s) which measures how far electrons diffuse in a solid without losing spin coherence. The important fact is that L_s is typically of the order of a micrometer that makes spintronics a viable option for future micro and nano electronics, because any information encoded in electron spin will spread undisturbed throughout the device. Clearly, the longer the spin life time, the better and more reliable will be the spintronic device. The study of spin relaxation is thus of great importance for spin-based technology. Recently, Sarma *et. al.* [24] have reviewed the current understanding of spin relaxation processes in electronic system.

The initial measurements of spin lifetime were conducted in metals like Na or Li by conduction electron spin resonance technique [25]. The most important outcome of these experiments is concerned with the magnitude of T_1 and its temperature behaviour. It is observed that T_1 is constant at low temperatures (say below 50 K) and increases linearly with increasing temperature above 200K. These two observations helped to shape the theoretical understanding of processes behind spin relaxation in metals. It is now widely accepted [26] that electron spin in metals (nonmagnetic) decays by scattering, presence of impurities and phonons. In other words, conduction electrons loose memory of their spin orientation through interaction with phonons, other electrons and impurities.

The crucial interaction which provides the necessary-spin dependent potential, is the spin orbit interaction. The spin orbit interaction is a relativistic effect which can have various sources being the interaction between electrons with impurities and ions (nuclear spin) [27]. However, the electron spins are promising medium for information storage that follows from the large value of the factor T_1 / τ, where τ is the momentum relaxation time. A crude estimate of T_1 [28] is $T_1 \approx \tau / b^2$, where $b \approx V_{SO} / E_F$, with V_{SO} denoting an effective strength of the spin orbit interaction, and E_F the Fermi energy. Since $V_{SO} << E_F$, it follows T_1 that $\tau >>1$. Now the question is, for how long an electron can travel in a solid state environment without flipping its spin. Is there any limit for T_1. In an ideal impurity-free sample, T_1 would approach infinity as temperature gets to absolute zero. Thus, a recipe to increase T_1 at low temperature is to produce very pure sample. It is also found [29] that the tailoring of spin relaxation can also be possible as T_1 can be changed by orders of magnitude by doping, straining, alloying or the changing dimensionality.

(ii) Giant magnetoresistance :

Magnetism is an intrinsic physical property associated with the spin of electron material. If the spin of electrons are aligned (i.e. all spin-up or all spin-down), it creates a large-scale net magnetic moment as seen in magnetic material like iron and cobalt [30]. We can exploit these magnetic moments in the recording devices like computer hard disks and other memory based devices [31]. Datas are recorded and stored in tiny areas of magnetised magnetic material. To access the information, a read head detects the minute change in magnetic field as the disk spins underneath it. This induces corresponding changes in the head's electrical resistance (magnetoresistance).

The idea of spintronic devices remain hidden till the discovery of the powerful effect called Giant magnetoresistance (GMR) [32]. This GMR results from the subtle electron-spin effects in ultra-thin multilayers of magnetic materials, which cause huge changes in their electrical resistance when a magnetic field is applied. GMR is approximately 200 times stronger than ordinary magnetoresistance. These materials would be able to sense much smaller magnetic fields, allowing the storage capacity of a hard disk increase by 10~20 times.

The basic GMR device consists of a three-layer, out of which a magnetic material layer is sandwiched in between two nonmagnetic material layers, for example one cobalt layer is sandwiched between two Al or Cu layers [33]. The electron supplied by the external current will pass through these layers only when its spin orientation is parallel to that of the magnetic material. Otherwise, electron will be back scattered. Thus GMR device acts as a spin filter or spin valve. The spin orientation of the magnetic material can be altered by supplying external magnetic field and hence, it is used in sensing technology. The developed GMR sensors have wide range of applications which include

(i) Fast accurate position and motion sensing of mechanical components in precision engineering and in robotics,

(ii) All kinds of automotive for handling, antiskid systems, speed control and navigation

(iii) Missile guidance ;

(iv) Key-hole surgery and post-operative care.

Recently, thin film [34] heads of Giant magnetoresistive (GMR) for hard disk drives (HDDs) has been developed with a real recording density of 15 Gbit/inch^2. In accordance with increased use of multimedia in information equipment, HDD capacity have grown at a startling pace more than tenfold over the past five years. Now, the magnetoresistive (MR) heads are gradually being replaced by GMR heads, which offers more sensitivity and higher density magnetic heads in HDDs.

(iii)Spin-polarized transport :

The devices based on charge application have been extensively investigated, and transport in these devices is well understood for both hetτerostructure and inhomogeneous materials. But how the spin degree of freedom will behave in transport across interfaces in a heterostructure or through inhomogeneous materials [35-37] ? With the prospects of making spintronics device [1,2] which consists of hybrid structures, it is necessary to understand the influence of interfaces between different materials. This is an important issue as some of the proposed spintronics device [3] relies on the direct electrical spin injection from a ferromagnet to a semiconductor [38,39]. This situation is complicated by the possibility of spin-flip scattering at magnetically active interfaces. In a wide variety of semiconductors, the main source of interfacial scattering at interface with normal metal are arising from the formation of an active Schottky barrier [40] and there exists a difference in the carrier density in these two materials [41-43]. On the other hand, the absence of spin polarized carrier leads to reduce the interfacial transparency. Hence, these considerations should be included while assessing feasibility of various spintronic devices.

A basic requirement for transporting electron in a spintronic device needs the production of large spin-polarized current in electronic materials (semiconductors) and to sustain it for longer time period. However, introduction of spin-polarized current possess few difficulties in semiconductor devices. These problems can be overcome by the development of advanced materials like GaMnAs, InMnAs, *etc.* [44]. In the past, various semiconductor-based hybrid structures relied on ferromagnets to provide spin polarization. Now-a-days, there are alternative ways available to create spin-polarized carriers and their transportation in a semiconductor. An important obstacle to develop semiconductor-based spintronic device [3] is to achieve direct spin injection from a ferromagnet [45]. However, there are some theoretical [46] limitations for achieving higher degree of spin polarization. These are (i) consequences of working in a diffusive regime and (ii) the current conversion near the ferromagnet/semiconductor interface.

Further, the fabrication of hybrid structure which combine a semiconductor (Sm) and a superconductor (S), would allow the investigating spin transport effectively [42,44]. Such hybrid structures would also help in determining the degree of spin polarization in an extrinsically induced carrier in the semiconductory layer. In this, a two-particle process takes place; an incident electron, together with a second electron of opposite spin (with their energy $\approx 2E_F$) is transferred across the interface into superconductor where they form a Cooper pair. There are some theoretical studies of spin-polarized transport in a Ferromagnetic and high-temperature superconductor [42,47,48]. Experiments performed with highly polarized ferromagnets suggest that the surface spin polarization decreases faster with temperature than the corresponding bulk spin polarization [49,50].

The case where these ideas are implemented is a direct electrical spin injection from ferromagnetic into non-magnetic superconductor. This is also an ingredient needed to implement various proposals for hybrid semiconductor devices, such as the spin transistor of Datta and Das [3].

(iv) Spin transistor :

The high mobility field effect spin transistor has been shown in Figure 2, which is based on the scheme of Datta and Das [3]. The heterostructure (InAlAs/ InGaAs) provides an inversion layer channel for two-dimensional electron transport between two ferromagnetic electrodes. One acts as an emitter and the other as collector. When the emitter release the electrons, the collector acts as a filter by allowing the electrons having spin orientation parallel to the spin of collector material. In the absence of spin relaxation and spin -dependent processes during transportation, every emitted electron enters the collector. The perpendicular field at the heterostructure interface, however induces a spin orbit-like interaction, which acts as an effective (momentum dependent) magnetic field, in the direction perpendicular to both the transport direction and the direction of the heterostructure field (perpendicular to the page). This field leads to spin precession of the electron. Depending on the amount of the electron spin in the direction of the collector magnetization, the electron current is modulated: an electron can pass through only when its spin is parallel to the magnetization. Spin FET would have several advantages over conventional FET *e.g.* flipping an electron's spin takes much less energy and can be done much faster than pushing an electron out of the channel. One can also imagine an additional type of control by changing the orientation of the source or drain with a magnetic field, which is not possible with a conventional FET. So far, no one has succeeded in making a working prototype of the Dutta and Das spin FET because of the difficulties in efficiently injecting spin current from a ferromagnetic metal into a semiconductor.

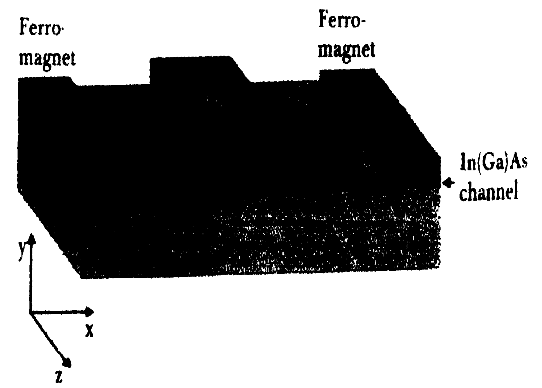

Figure 2. Datta & Das spin transistor. An injection-detection with a metallic fate for field induced spin-orbit coupling.

(v) Spin valves :

Spin valve is a device in which spin-dependent transport through a tunneling junction takes place. These systems currently attract much attention due to its possible applications in magnetic and magnetoelectronic devices [1,30,51]. Solid-state memory devices based on magnetic structures, retain their state when voltage is removed. This has been a driving force in the development of non-volatile electronic memories which could offer the benefit of higher read/write cycle endurance and longer retention time. The key feature of this device is that the resistance of the sandwiched material is different for aligned and anti-aligned magnetization orientations.

A spin valve in general, consists of a GMR trilayer [51]. In these systems, current switch are controlled by flipping the spin of one magnetic electrode. The structure of spin valves consists of various layers in which one layer is magnetically soft (it is very sensitive to small fields) and other is magnetically hard (it is insensitive to fields of moderate size) by various schemes. As the soft free layer moves around due to applied field, the resistance of the whole structure will vary. The magnetic random-access memory (MRAM) devices based on spin-valves proposed by IBM [52] are claimed to be first-ever integrated magnetic multilayers with semiconductor devices in a single bit cell MRAM uses magnetic hysteresis to store data and magnetoresistance to read data. MRAM data access times are about 1/10,000 that of hard disk drives. MRAM is not yet available commercially but production of at least 4-MB MRAM is anticipated within a year or two.

(vi) Spin filter :

In hybrid structure, the presence of magnetically active interfaces can lead to spin-dependent transmission [35-37]. This spin-dependent transmission allows an electron of particular spin orientation (up or down) to pass through the barrier and blocks the other orientation. This feature of hybrid structure helps in filtering the spin. Besides these hybrid structures, there are other structures which can be used as a spin filter, for example quantum dots. Recently, Recher *et al* [4] have proposed a quantum dot set up, which can be operated either as spin filter (spin diode) to produce spin-polarized current or as a device to detect and manipulate singlet spin state (single spin memory) [1,53]. For this, they have considered a quantum dot in a Coulomb blockade regime [54] under sequential co-tunneling processes. They have proposed that the spin degeneracy is lifted [4], with different Zeeman splitting in the dot and in the leads, which then results in Coulomb blocked peaks that are uniquely associated with a definite spin state on the dot (in the Coulomb blockade regime, the charge on the dot is quantized. The process of spin filtering on a dot-lead based system is shown in Figure 3. In this, a spin -down electron tunnels from lead 1 to the dot, forming a singlet, and tunnels out again into lead 2. Tunneling of spin-up electrons into the dot is forbidden by energy conservation since this process involves excited states. Hence in the specified regime, dot acts as spin filter through which only spin-down electron can pass [4].

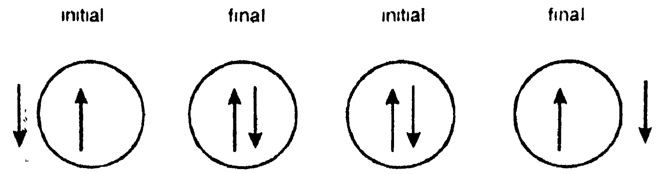

Figure 3. A schematic diagram corresponds to a quantum dot spin filter The spin on leads is shown by bare spin and on quantum dot is represented in encircled spin

4. Spin-based quantum phenomena

One of the most ambitious spintronic devices is the spin-based quantum computer in solid-state structures. The purpose of quantum computer (QC) is obtained by the use of electron or nuclear spin. In this section, we shall discuss spin-based quantum computation, quantum information processing, quantum communication and quantum networks.

(i) Quantum computation :

Spin-based quantum computer (QC) is the most revolutionary concept among all the possible spintronics devices [15, 55-60]. In QC, either electron spin or nuclear spin is used as the building blocks. The spin-up and spin-down state of an electron or a nucleus provide the quantum bit (qubit), analogous to '0' or '1' in a classical computer (CC). However, spin which obeys the laws of quantum mechanics can not have only up and down states, but also arbitrary superposition of these two states. This inherent parallelism and other quantum mechanical properties such as entanglement and unitary evolution distinguish QC from classical computer (CC).

A central issue of quantum computing is to develop algorithms that take advantage to process information faster than the best classical computers can. Unlike the CC, the QC handle more inputs with less number of qubits, so quantum computation algorithm are much faster. The increased number of input not only leads to an enormous increase in computation time but also limits the hardware, which makes the CC behind [61].

The main goal of quantum computer is to change the exponential CC time into polynomial QC time. Closest to this goal comes up till now is Shor's Algorithm [55]: it would allow a quantum computer to find the prime factors of a large number in polynomial time. For classical computers, no such algorithm is known: finding the factors, *e.g.*, a thousand-digit number would take much longer time than the age of the universe using today's classical computers, while a quantum computer might find them within seconds. The second major quantum algorithm is Grover's Algorithm [56] which finds a marked item in an unsorted database containing N entries with about square root of N queries to the database. On a classical computer, the best algorithm needs on the order of N queries.

In search of appropriate model for a QC, many proposals have been put forward. There are proposals [17,59,60,62] suggesting quantum dot-trapped electron spin as qubits. In this, a single electron is trapped in a gated horizontal GaAs quantum dot, with pulsed local magnetic field and inter-dot gate voltage governing the single qubit and two qubit operation. Vrijen *et al* [63] proposed that donor electrons replace the quantum dot electrons in a compositionally modulated SiGe alloy. They suggested that on varying the gyromagnetic ratio, allows electron spin resonance for single qubit operations and exchange interaction for two qubit operations. One important advantage of electron spin is their 'maneuverability' ; electron are mobile and can be manipulated by both electric and magnetic fields.

Beside these electron-spin based QC models [18], there are some nuclear-spin-based proposal, such as the one using nuclear spin of phosphorous donor atoms embedded in silicon treated as one qubit. Here, spin 1/2 donor nuclei are qubits, while donor electrons together with external gates provide single-qubit using external magnetic field and two-qubit operations using hyperfine and electron exchange interaction between the neighboring spin. The donor electrons are essentially hop between different nuclear qubits and controlled by external gate voltages (*i.e.* external gates are used to tune the nuclear magnetic resonance frequency, and donor electrons are the intermediaries between neighboring nuclear spins). In addition, the final measurement is also over donor electrons by converting spin information into charge information [64]. The main advantage of nuclear spin qubit is their exceeding long coherence time, which allows many coherent operations. In general, nuclear spins have very long coherence time because they do not strongly couple with their environment, and are thus good candidates for qubits. However, this isolation from environment also brings with it, the baggage that individual nuclear spins are difficult to control.

Another scheme [65] based on nuclear spin states of molecules in solution, has been proposed for the development of the liquid state Nuclear Magnetic Resonance (NMR) computer. They have demonstrated a 5-qubit order finding algorithm. However, the NMR quantum computer have scalability problem, since the signal to noise ratio decreases exponentially as the size of the molecule increase.

Recently, Sousa *et al* [66] have calculated the effect of an inhomogeneous magnetic field on the exchange energy of a double quantum dot artificial molecule, projected to be used as a 2-qubit quantum gate in a quantum dot-quantum computer. They have concluded that exchange interaction changes slowly in the presence of inhomogeneous magnetic field.

The major difficulties facing in various QC models are achieving precise control over unitary evolutions and maintaining quantum mechanical coherence. In the traditional electronic devices deal with large numbers of electrons at a time, while in spin-based QC one has been able to precisely control spin of individual electrons. Furthermore, the electron spin need to be essentially isolated from their environment so that there dynamics is governed by quantum mechanics. If this isolation is imperfect, the spins quantum information will leak into their environment, and the dynamics of the spins will become irreversible and classical, so that the QC operation will be disrupted. It is also believed [15] that large-scale experimental quantum computing would be impossible because of the fragile nature of quantum information. However, this concern has been largely resolved by the development of quantum error correction (*i.e.* quantum information can be encoded in such a way that potential error can be detected and corrected) and fault-tolerant quantum computation. The theory of quantum error correction and fault-tolerant quantum computing has been developed to overcome this difficulty [67-69].

(ii) Quantum information and processing :

The advent of quantum information processing has given birth to a great deal of new thinking about how to create physical computing device that operate in the unexplored quantum mechanical regime [70-72]. The efforts are now underway to produce working laboratory devices that perform quantum mechanical-based information processing.

It was observed already in the 1960's by Rolf Landauer [73] that information is physical *i.e.* information cannot be separated from physical representation: it is always stored in some physical system, manipulated by some physical process. This observation has number of consequences for information theory. Perhaps, the most striking one is that it makes a big difference whether the information is stored and processed in classical or quantum mechanical systems.

In a system governed by classical physics, one bit of information could take either of two states, for example a piece of magnetic tape being magnetized 'up' or 'down' representing the number '0' and '1', respectively. Benioff and others [74] have observed that the quantum mechanics might provide new and possibly very powerful ways to process the information. Moreover, at the current pace, the ongoing miniaturization in chip design in the next decade, will lead to chip components so small to ensure the importance of quantum mechanics.

In quantum computation, information would be stored in quantum mechanical two state systems, so called qubit [75]. The most peculiar feature of a qubit (and all quantum systems) is the existence of superpositions: according to the experimentally well established superposition principle, a qubit which can be in two distinct physical states (say '0' and '1') can also be in an arbitrary coherent superposition of these states, representing in certain sense both numbers at the same time

(Figure 4). For example, in a conventional computer, every bit has a definite value of 0 or 1. A series of eight bits can represent any number from 0 to 255, but only one number at a time. Electron spins restricted to spin up and spin down, can also be used as bits. Quantum bits, or qubits can also exist in superpositions of 0 and 1, that can represent both numbers from 0 to 255 simultaneously [76]. Electron spin are natural qubit; a tilted electron is a coherent superposition of spin up and spin down and is less fragile than other quantum electronic states. Similarly, two qubits can be in a superposition of the four states 00, 01, 10 and 11. These states are generally entangled *i.e.* they cannot be written as a product of the states of two individual qubit. The general state of n qubits is specified by superposition of 2^n numbers. With suitable algorithms, a quantum computer can make use of this: it can process all those numbers at the same time. This exponential (*n* qubits provide for 2^n numbers) quantum parallelism is the basis for the quantum speed up in Shor's [55] or Grover's algorithms [56]. Moreover, the superposition principle is the basis for the quantum phenomena of entanglement that is of particular importance for quantum communication.

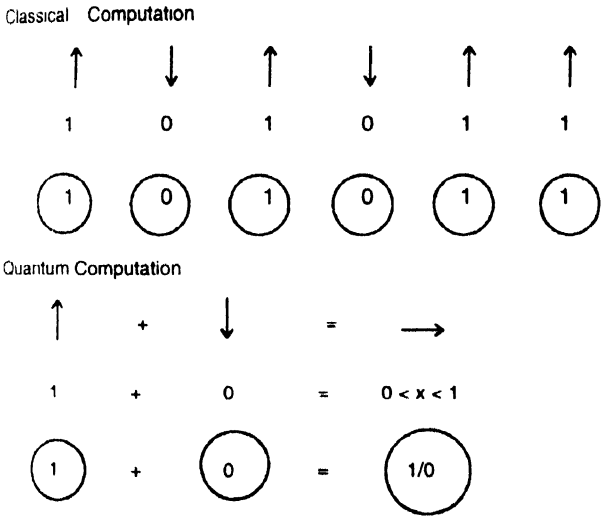

Figure 4. The role of spins in classical & quantum computation. In classical computation, every bit has a definite value 0 or 1 but quantum bits or qubits can exist as superposition of 0 and 1.

(iii) Quantum communication :

The quantum communication is a subfield of quantum information processing which is concerned with the exchange of information between distant users [77]. The key tool for quantum communication tasks is quantum teleportation [78]. By this process, the quantum information (*i.e.* the state of quantum system) can be sent to a distant location even without transporting the actual system. The crucial records needed for teleportation is a pair of quantum mechanically correlated (entangled) quantum systems shared by the communicating users. When this is available, local quantum operations and classical communication are sufficient to send quantum information. Several applications of quantum mechanics to communication [79] problems have been proposed, ranging from more efficient ways of sending classical information (dense coding) over algorithm that reduce the complexity of communication problems to novel ways.

(iv) Quantum networks :

The full power of quantum information processing is attained when quantum computing devices and quantum communication are connected to form a quantum network. Therefore, it is important to have a good interface between quantum computers and quantum channels. Until now, work in this area considers the nodes of the network to be realized by quantum computers based on trapped ions (atoms) that were first proposed by Cirac *et al* [80]. One reason why these systems have been favoured in this context is that they interact in a well-understood and controllable fashion with photons, which are the best carriers of quantum information. To design a quantum interface, it is required to find a physical process that maps the internal quantum state, *e.g.* an ion on to the state of the light field and *vice versa.*

5. Future technology

Advancement has been made towards the realization of electronic computers integrated on the molecular scale (moletronics) system. It has been demonstrated that individual molecules can serve as incomprehensibly tiny switches and wires, which are one million times smaller than those on conventional silicon microchips [81-84]. This has resulted very recently in an assembly and demonstration of tiny computer logic circuits built from such molecular-scale devices [85-88]. One of the promising materials, which are important in the advancement of future molecular scale, is carbon nanotube [89]. Currently, researches are debating over the motion of electron along a nanotube structure. It is observed [78] that in defect-free nanotubes, electron can travel without any scattering that gives metal wires their resistance. When electrons travel long distances without scattering, they, maintain their quantum states, which is the key to observing effects such as the interference between electron waves. A lack of scattering may also help to explain why nanotubes appear to preserve the 'spin' state of electrons as they move. This unusal behaviour of nanotubes is important to construct spintronic devices that switch on or off corresponding to electron's spin.

However, spin-dependent transport in a carbon nanotube magnetic tunnel junction was recently investigated experimentally with two cobalt leads attached to a nanotube [90]. The data showed that the nanotubes have a spin-scattering length of at least 130nm, making them good candidates for molecular-scale magnetoelectronics devices in which both the charge and the spin degrees of freedom are utilized. The spin-coherent transport through a carbon nanotube coupled to two ferromagnetic leads was examined theoretically by Mehrez *et al* [91], who observed a clear spin-valve effect, charterized by minimum resistance, when the magnetization axes of the two leads are parallel and maximum when they are antiparallel. Physically, this variation in the resistance is a reflection of the differences in the majority and minority carrier concentrations in the ferromagnetic material.

Recently, Orgassa *et al* [92] have discussed a new approach to magnetic imaging, using a carbon-nanotube tip and demonstrated spin transport through a multiwall carbon nanotube over a distance of $1 \mu m$. For magnetic imaging, they have used spin-resolved scanning tunneling microscopy (SR-STM). This device is based on the recently observed magnetoresistance effect [93] in a carbon nanotube contacted by ferromagnetic electrode. These nanotubes-based devices can also be utilized as random access, non-volatile memory devices [94]. However, nanotube itself is a big subject, which is beyond the scope of this review.

The other molelectronics-based devices in future, can be fabricated on the chip consisting of DNA molecules [95, 96]. The experimental studies indicate that DNA behaves as a metallic conductor, semiconductor, or an insulator according to different contacts, molecular lengths and ambient surroundings [97]. Recently, Porath *et al* [98] have described a model in which they have sandwiched a DNA molecule between ferromagnetic contacts like Ni and Fe. Their results suggest that the transport in this device occurs when the electronic levels of DNA molecule align with the quasi-Fermi levels of electrodes. Zwolok *et al* [95] have theoretically studied the spin-dependent transport properties like spin-valve behaviour in a device containing F/DNA/F. This study provides new insight to the fundamental mechanism of electronic transport in DNA through spin and also broadened the possible application of DNA as component of spin based molecular electronics.

6. Summary and outlook

In summary, we have reviewed recent advances in spin-based electronics devices and quantum computation. The progress in this field is extremely rapid, as evident by the large numbers and quality of scientific studies, and also by the growing number of applications. However, the progress towards the understanding and implementation of spin degree of freedom in metallic multilayer and semiconductor is 'gaining momentum'. On the other hand, spintronics read head sensor are already impacting multibillion dollar industry and magnetic random access memory using metallic element will soon impact the industry.

However, current QC technology is limited to fewer than 10 qubits and the testing of simple algorithm [99], but quantum computation of the next generation, with 10-100 qubits is a challenging task that will be helpful in solving hard problems of quantum many body theory. Moreover, we need theoretical understanding of efficient algorithm that could enable us to understand the problems of finite system such as applicability of BCS model to mesoscopic state and nuclear systems. However, researchers are trying to find out low-lying spectrum of pairing models with long-range quantum computers of next generation (10-1000) qubits) [100].

Much remain to be understood about the behaviour of electron spin in materials for technological applications, but much has been accomplished. Now experimentalists are taking up the fundamental challenges of creating and measuring spin, understanding better transport of spin at interfaces and clarifying the types of errors in spin-based computational systems. Tackling these will help in developing new experimental tools and broaden considerably our theoretical understanding of quantum spin. However, the control of spin and its manipulation for ultra small structures is to be understood. We are working in this direction to understand the role of spins in ultra- small structures for example, carbon nanotube quantum dots. The proper understanding of these will be an entirely new world of spin technology with new capabilities and opportunities.

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